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Research and Development Technical Report

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COMPUTER FAMILY ARCHITECTURE SELECTION COMMITTEE -  
FINAL REPORT, VOLUME VIII - CFA FINAL SELECTION

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September 1977

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Computer Family Architecture, Military Computer Family, Absolute/Quantitative Criteria, Life Cycle Costs, Virtual Machines.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) → The Computer Family Architecture (CFA) final selection process was divided into four phases: (1) a. Data Review. Data developed by the CFA Selection Committee in connection with initial absolute/quantitative criteria, architecture test results, support software evaluation, licensing terms/conditions and life cycle cost analyses were reviewed and summarized.		

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20. <sup>2</sup>b. Manufacturers' Presentation. Representatives of each finalist were invited to give brief presentations about future plans for their architecture. Questions from the Committee probed areas of concern.

<sup>3</sup>c. Discussion. The discussions centered around contributing factors, both pro and con, to the selection of each architecture.

<sup>4</sup>d. Summation. Each Architecture Subcommittee chairman provided a summation of the case for selection of his architecture.

The Committee had four final recommendations.

a. The Committee unanimously agreed that a single instruction-set architecture should be selected for the MCF, that the selection of only one architecture is more important than which one is selected, and that any one of the three final candidate architectures could provide a satisfactory basis for the MCF.

b. The DEC PDP-11 was determined to be the most advantageous architecture for the MCF, the IBM S/370 was ranked second, and the Interdata 8/32 was ranked third.

c. The Committee agreed that an effort should be made to correct the limitations of the selected architecture.

d. A single organization structure must be established to control the architecture, otherwise major incompatibilities between different implementations will surely result.

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## 1. INTRODUCTION

In order to understand the CFA final selection process, it is first necessary to examine how the general goals of the entire program were embodied in the approach taken to the final selection. The stated purpose of the CFA program was to select a single computer architecture as a standard for the Army and Navy and then implement a family of upward compatible machines based on that architecture to meet specific cost/performance needs of various military applications. By pursuing such a program, the Army and Navy would ultimately benefit in terms of reduced software costs through the use of a common base for software development and the ability to apply new technology to gain cost/performance improvements. The basis for selecting an architecture for consideration as an Army/Navy standard was that it be a current, well used, understood, supported and documented commercial or military architecture. The underlying assumption was that the most important facet of an architecture was its general usability and support base given that it meets certain technical criteria.

In light of these general goals, a choice of any one of the three finalists would have been satisfactory. The CFA final selection process, however, also attempted to determine which one of the three finalists, if selected, would be the most cost effective for the military. The Committee's problem was, therefore, not to determine which of the finalists was "best" in absolute terms assuming all possible computing environments, but rather to measure the military data-processing environment and then to determine the candidate that would fit it best.

The first task of the final selection process was gathering information about the final candidates, and military computing needs. To accomplish this task, four subcommittees were established to examine architectural-performance parameters, licensing arrangements, software bases, and life-cycle costs over the projected life of the project.

The final selection process was divided into four phases:

- a. Data Review. Data developed by the Committee in connection with initial absolute/quantitative criteria, architecture test results, support software evaluation, licensing terms/conditions and life cycle cost analyses were reviewed and summarized.
- b. Manufacturers' Presentation. Representatives of each finalist were invited to give brief presentations about future plans for their architecture. Questions from the Committee probed areas of concern.

- c. Discussion. The discussions centered around contributing factors, both pro and con, to the selection of each architecture.
- d. Summation. Each Architecture Subcommittee chairman provided a summation of the case for selection of his architecture.
- e. Recommendations. This report considers each of these phases in the next four sections. The final section outlines the vote and recommendations of the Committee.

## 2. DATA REVIEW

### a. Overview

The data developed by the Committee were summarized and presented as shown in Tables 1 and 2 for the absolute/quantitative criteria (used to screen out three CFA finalists from a list of nine candidates) and for the above-described other data, respectively. Each of the items in Tables 1 and 2 is discussed below in the following subparagraphs.

### b. Absolute/Quantitative Criteria

In order to select three CFA finalists from the list of nine candidate CFA's, the Committee established a set of absolute and quantitative criteria for ranking the CFA candidates. Data on each candidate CFA were provided by an architecture subcommittee and were audited to ensure equitable architecture evaluation. Summary results are shown in Table 1 wherein the CFA candidates are listed in the order of their ranking by the quantitative criteria with remarks concerning their absolute criteria evaluation. As a result of this screening process, three CFA finalists were selected for further evaluation: Interdata 8/32, DEC PDP-11, and IBM S/370.

### c. Architectural Test Results

One of the major questions raised during the selection process was the relative capabilities of the finalists in implementing characteristic problem solutions. If tests indicated that one architecture needed significantly less memory and processing power to execute a task, it would be possible to say that the hardware costs associated with implementing that architecture would be less than for the others. The approach taken to answer this question was to describe the programming level of each of the finalists using the ISP notation. A simulator for each

ARCHITECTURE	QUANTITATIVE CRITERIA	ABSOLUTE CRITERIA
INTERDATA 8/32	1.68 (BEST)	Problem with interrupts and traps
PDP-11	1.43	Passed all
IBM S/370	1.36	Passed all
AN/GYK-12	.94	Failed floating point
ROLM/NOVA	.92	Failed virtual memory mapping and interrupts/traps
B6700	.91	Failed protection
SEL-32	.86	Failed virtual memory mapping
AN/UYK-7	.46	Failed floating point
AN/UYK	.44 (WORST)	Failed protection

Table 1. CFA Candidate Scores on Absolute and Quantitative Criteria



QUANTITATIVE CRITERIA SCORES		TEST PROGRAM RESULTS		
		R	M	S
8/32	1.68	.83	.85	.83
PDP-11	1.43	.94	.93	1.00
S/370	1.36	1.29	1.27	1.21
SEE NOTE 1 BELOW		SEE NOTE 2 BELOW		

	SUPPORT SOFTWARE VALUE CURRENTLY AVAILABLE		DEFICIENCY
8/32	\$15.3M		\$25.9M
PDP-11	\$22.2M		\$19.1M
S/370	\$32.3M		\$ 9.6M

TOP DOWN COST MODEL (SEE NOTE 3) RELATIVE COST (S/370 = 1)		BOTTOM UP COST MODEL FOR 1985 RELATIVE #SYSTEMS PREF. COST (S/370 = 1) (SEE NOTE 4)	
8/32	1.23	1.00	----
PDP-11	1.07	.91	14.5
S/370	1.00	1.09	0.5

NOTE 1: These are relative values with an average value of one for nine CFA candidates. The higher the value, the better the architecture.

NOTE 2: These are relative values with an average value of one for the three CFA finalists. The lower the value, the better the architecture. S is a measure of the program storage required for test programs by each architecture. M is a measure of the processor/memory bandwidth to run the test programs, i.e. # bytes transferred between processor and memory. R is a measure of the internal processor bandwidth required to run the test programs.

NOTE 3: Top down cost model analyzed variation of DOD computer resource budget as a function of the selected CFA.

NOTE 4: Bottom up cost model analyzed variation of life cycle cost of 15 tactical data systems as a function of the selected CFA. Relative cost refers to total life cycle cost of all 15 systems. # Systems preferred indicates the number of systems with the lowest life cycle costs for each architecture. The ".5" denotes a tie between two architectures for one system.

Table 2. Final CFA Selection Data Summary



architecture was then obtained by compiling each description on the ISP compiler at Carnegie-Mellon University (CMU) in Pittsburgh. Test programs representative of military computing tasks were then run on these simulators. In order to characterize each machine's performance on these programs, values of three measures, S, M and R, were collected. These measures can be roughly defined as follows:

- S measure - A count of the number of bytes needed to store the instruction stream for a test program.
- M measure - The number of bytes transferred between the central processor and main memory during the execution of a test program.
- R measure - The number of register transfers, both internal to the central processor and visible to the programmer, needed during the execution of the test program.

The generation of the S, M, and R values for each architecture was controlled according to an experimental design devised at CMU. In accordance with this design, subsets of 12 test programs were assigned to 18 programmers both at CMU and Army/Navy labs and approximately 100 data points collected.

The results of the benchmark programming, simulation, and statistical analysis which formed the architectural test were presented and are summarized in Table 2. The physical interpretation given to these results was that, on the average, the IBM 360/370 architecture required approximately 20% more core and processing power than the PDP-11 and 40% more than the Interdata 8/32 to execute the test program set.

A study of the S, M, and R measures for individual benchmark programs pinpointed the relative weaknesses of each architecture. These weaknesses should be considered during the implementation plan of the Military Computer Family (MCF) architecture. In particular, the Interdata 8/32 performed uniformly well. The PDP-11 was comparable to the 8/32 in all benchmarks except the two that required large address spaces: the FFT and Quicksort. As reflected in the M measure, the PDP-11 typically took two to three times as many memory transactions (e.g., 15,000 to 9000 bytes for the FFT), as the Interdata 8/32. The S/370 was generally slightly worse than the other candidates. However, a significant difference was observed on the I/O benchmarks where the S/370 was a factor of 10-20 times worse than either the Interdata 8/32 or the PDP-11 (e.g., an M measure of 370 bytes to 30 bytes for I/O kernel).

The Architectural Test Failed to incorporate two factors that some committee members felt important: previous programmer experience with the architectures (i.e., there are many skilled S/370 and PDP-11 programmers but few 8/32 programmers), and the relative amount of programming time required for each benchmark as a function of architecture (i.e., two architectures being equal, one might be more difficult to program and require more time to produce a program of equal quality).

The statistical analysis showed that at the 95% confidence level (i.e., if the experiment was conducted 100 times, 95 of those times the results would be the same) the Interdata 8/32 was superior to the S/370. The PDP-11 was superior to the S/370 at about the 90% confidence level. At the 95% confidence level, the Architectural Test did not uncover any statistically significant difference between the PDP-11 and the Interdata 8/32. Since the Interdata 8/32 and PDP-11 were closely matched, the average of their values was used and shown to be superior to the S/370 at the 95% confidence level.

#### d. Support Software Evaluation

Another facet of each architecture considered significant to the evaluation process was the value of their respective software bases. Consideration of this factor was based on the notion that the more complete an architecture's software base was, the less the investment required by the military in that base and the more immediately useful the architecture. The approach taken was to consider the software base as a set of tools for use in developing applications programs. Included in this set were not only editors, linkers, compilers, and such, but also high level Data Base Management Systems, library packages and a number of different types of operating systems. This set, as a whole, was then presented to each member of the committee with the request that he rank them in accordance with their significance to his typical applications.

The results of the support software evaluation are summarized in Table 2. The value of the currently available support software base (in terms of the cost to develop it today) is shown in the lefthand column for the three CFA finalists. The support software base of each CFA finalist was compared with the desired software base as determined by committee vote. The value of the deficiency in millions of dollars is tabulated in the righthand column of Table 2. The result of the study was that existing support software base was greatest for the IBM S/370 and least for the Interdata 8/32. This result implied that if the IBM S/370 architecture were selected, then the needed investment in software tools would be less than for the other two architectures.

#### e. CFA Licensing Terms/Conditions

A somewhat difficult to quantify, but, nevertheless, very important issue was the willingness of every manufacturer to cooperate with the government, assuming his architecture was selected. While not a strictly technical issue, the undesirability of recommending an architecture of an unwilling manufacturer was recognized by the committee. In order to address this issue, a series of meetings were held with each manufacturer by selected representatives of the Army and Navy to inquire as to what the manufacturers might expect in return for the use of their architecture by the government, e.g., what kind of licensing agreement they would require. The results of these meetings indicated, both through each manufacturer's licensing requirements and their attitude during the meetings, that all three manufacturers were willing to cooperate, but that DEC showed the most interest and responsiveness. The details of the proposed

licensing agreements are given in Volume VII.

#### f. Life Cycle Cost Models

Although the above described information, along with the qualitative and quantitative criteria formed a sizeable data base on the CFA finalists, the actual impact of selecting any one of them on the military computing environment was unclear. The basic cause of this situation was the lack of a quantitative method to relate all of the above information (such as S, M and R measures) to the relative dollar cost to the Army and Navy of using a particular architecture. Without such a method, the selection of an architecture by the CFA committee might be difficult to justify to upper level DoD management. Recognizing this possibility, the committee determined to compare the CFA finalists on a life-cycle cost basis.

The life cycle cost analyses used two independently developed and distinct models of military computer resource requirements: the Top Down Model and the Bottom Up Model.

##### (1) Top Down Life Cycle Cost Analysis

The top down model involved calculating the relative cumulative cost incurred by each architecture over a time period of one to thirteen years beginning in 1978. The model used as inputs not only data gathered by the CFA subcommittees but also projections of trends in overall military requirements and dollar expenditures for both hardware and software, estimates of the impact of the available support software on software production costs, and estimates of the relative amounts spent on processors and memories. The model also considered the time value of money and architecture related parameters. The best architecture for a time period would be the one that produced the lowest relative cumulative cost over the development cycle. The relative life cycle costs are shown in Table 2 for the conditions where the hardware-to-software cost ratio is 1:1 in 1985 and the estimated support software investment for the selected CFA from 1978 on is \$2M annually. Table 2 indicated that the 1985 relative life cycle costs of PDP-11 and S/370 are comparable and approximately 20% less than the 8/32 cost.

##### (2) Bottom Up Life Cycle Cost Analysis

The major difference between the second, or bottom up, model and the top down model lies in the data used for inputs. Whereas the top down model used estimates and projections of trends in military computing requirements and expenditures, the bottom up model attempted to use a



number of current military computing applications as representative examples of future requirements. Fifteen Army embedded computer systems ranging in size from small fire-control to large data-base management systems were used as the basis for the Bottom Up model. Each system was characterized in terms of memory and secondary storage requirements, processor power, number of installations, and various other system parameters. The data were then combined in the model with certain architectural parameters in order to determine which architecture would be most cost effective for each system. The total life cycle cost for each system and for all 15 systems was estimated for 1976 and 1985 procurements. Table 2 indicates the relative total cost and the number of systems for which each architecture provided the lowest life cycle cost. Table 2 is based upon the conditions where the average applications software cost per instruction in 1976 is \$34 (corresponding to a hardware-to-software ratio of 1.2:1 in 1985) and the estimated support software investment for the selected CFA from 1976 on is \$2M annually. Table 2 indicates that the PDP-11 had the lowest total cost by approximately 13% and the largest number of system preferences on the basis of individual system life cycle cost.

Limited sensitivity analyses of both life cycle cost models were made with respect to hardware-to-software ratio, support software annual investment and whether or not weighting was applied to the architecture test measures S, M, and R. The comparative life cycle costs of the three architectures were examined over a range of parameters: 1985 hardware-to-software ratios of 1:1 to 2:1; annual support software investment of \$1M, \$2M and \$3M; weighted or unweighted architecture test measures in the bottom up model; and 1976 to 1985 hardware cost ratio of 10:1 and 5:1.

In other words, the 8/32 looked like a good choice and the S/370 looked like a poor choice with assumptions which maximize the cost of hardware, and minimize the cost of software, while the S/370 looked like a good choice and the 8/32 looked like a poor choice under those assumptions which maximized the importance of software costs. The PDP-11, however, looked like a good choice in the mid range of assumptions and neither best nor worst in the extremes. Given the uncertainties of the input data and assumptions, the results of the two models appeared to agree reasonably well, and the relative closeness of the three architectures indicated that all three would be comparable choices in terms of life cycle cost.

### 3. MANUFACTURERS' PRESENTATION

Each manufacturer of a CFA finalist was invited to give a talk on the future plans for their architecture. Since the manufacturers did not hear each other's presentations, the results are not comparable. However, a number of interesting issues were raised that contributed to the final selection. The presentations are summarized below.

a. DEC

The PDP-11 family currently comprises 13 processor models spanning a cost range greater than 100:1. This exemplifies the implementation versatility of the PDP-11 as well as DEC's commitment to perpetuating the architecture. New product announcements include a Commercial Instruction Set (CIS), a Program Logical Address Space (PLAS), and DECnet. PLAS is a software system that automatically manages address mapping registers for user subroutines in an attempt to make the 16-bit address space appear as large as 24 bits. DECnet is a network protocol and associated software that allows different DEC operating systems, perhaps running on totally different architectures (e.g., PDP-10, PDP-11, PDP-8), to communicate.

DEC has traditionally been noted for supplying interfacing information and documentation to users. This practice should be helpful for designers of military embedded-computer systems.

Two areas of concern were explored by the committee during the question and answer period. The first was Floating Point Instruction Sets (FPIS). The PDP-11 family has two different FPIS: a four instruction set that takes its operands from the stack and is implemented in low end PDP-11's, and a full FPIS that is incorporated in a special floating-point processor, complete with single and double precision floating-point registers. The high-end PDP-11's have the full FPIS but do not implement the four instruction set in hardware (they could be handled in software via unimplemented instruction traps). DEC has not felt market pressure to make both FPIS's available in high level machines. If the PDP-11 is selected, the two FPIS problems should be considered in the MCF implementation plan.

The second concern was the small 16-bit physical address space in the PDP-11. DEC would only assure us that a solution to the limited address space problem would be marketed before the end of the decade. Again, this topic should be pursued in careful detail in any MCF implementation plan. On the whole, DEC seemed eager to cooperate and have their architecture selected.

b. IBM

Two interesting comments were made by IBM. The first was in effect, "We are not here to encourage or discourage the selection of the S/370." This eventually led to some concern by the committee about IBM's eventual cooperativeness and helpfulness if the S/370 were selected. The other comment concerned the level of standardization IBM will maintain across future models of the S/370. Basically, IBM is committed to holding the machine as seen by nonprivileged programs (e.g., problem state) invariant. Changes can be made to anything below the user interface with the operating system (OS). The manner in which portions of the OS are implemented, whether in software, firmware (microcode), or hardware, is open to future

change. In particular, the I/O architecture is not guaranteed to remain invariant. This posed an interesting dilemma for selection of the S/370 as the MCF CFA. The selection committee had decided to standardize on the instruction-set architecture and not the problem state architecture. If the S/370 were selected and its instruction-set architecture implemented, a risk would be run that, in the future, IBM might diverge. The MCF might not be able to capitalize on future IBM software. Furthermore, as IBM phased out support of its old software (since the instruction set was not the same as new IBM architectures) DOD would have to take over its maintenance and improvement.

In addition, if the S/370 were selected and the problem state architecture standardized on, another problem arises. In order to operate, the problem state needs run-time support from the OS, particularly in the area of I/O. IBM estimated that run-time support would be at least 5K of instructions. Further, any given I/O request would require the execution of about 1200 to 3600 instructions (at 1 microsecond/instruction that means an I/O interrupt response time on the order of 1-4 milliseconds). Not only would I/O response time be slow, but small tactical applications would have to carry along an extra 5K of memory for run-time support. Of course, solutions can be found, but the tactical MCF would no longer be compatible with the S/370.

#### c. Interdata

Interdata's presentation was primarily a review of the technology used in the 8/32 system. A floating point box has been delivered for an 8/32. They stated that they did not feel that technology was here yet to implement an LSI version of the 8/32. This comment leads to some concern about the applicability and cost effectiveness of the 8/32 architecture in small tactical-systems.

### 4. DISCUSSION

Two global concerns were expressed that apply to all architectures: family planning and virtual machines. The following sections treat these issues first and then give other comments grouped by machine.

#### a. Family

By careful family planning, IBM has attempted to insure the transportability of user programs between machine models. While not 100% successful in this goal, IBM has over 15 years of experience and has come closer to the transportability goal than any other manufacturer.



DEC has built a family of PDP-11's, but there are know incompatibilities in the instruction sets. Certain instructions execute differently on different machines. If there is no canonical PDP-11, then all the software may not be transportable throughout the MCF. Family consistency requires careful planning (IBM has a full-time staff of 12 professionals whose sole job is to insure family consistency).

The Interdata 8/32 has not really faced the problem of family planning. There is a 16-bit version of the 8/32, but compatibility is enforced at the assembly language level and a program must be reassembled to run on the other machine.

b. Virtual Machines (VM)

Some members of the committee felt that it was essential that the MCF support virtual machines. A VM system gives each user what appears to be a complete, independent machine, and permits different applications programs running under different operating systems to co-exist on the same physical hardware. Some concern was expressed about the applicability of VM's in tactical situations due to the VM overhead.

IBM has delivered a VM system. Although DEC has a hardware option that makes the PDP-11 virtualizable, DEC has not developed any software support of a VM. Interdata has not considered the problem.

c. DEC PDP-11

Concern continued to be expressed over the small address space of the PDP-11 and its ability to handle large problems. It was pointed out that future military systems will be distributed and that large address spaces may not be a problem. It was also noted that a substantial amount of work on distributed, multiprocessor systems has been done utilizing the PDP-11. In any event, the small address space was explicitly tested by two of the test programs. Even with the degradation in performance on these programs, the difference between the PDP-11 and the 8/32 was not statistically significant at the 95% confidence level. The PDP-11 has good I/O characteristics and was originally designed for the small applications area.

d. IBM

Poor I/O interrupt response remains a key issue with regard to the S/370. The test programs underline this deficiency. Also, it is unclear whether the I/O structure can be subsetting in a compatible manner for tactical systems. It was pointed out that IBM has built an advanced aerospace computer of small size and weight which is 360 instruction-set compatible at the problem state level.



IBM let it be known that it would not provide their architectural verification programs to DOD. However, IBM was the only one of the three manufacturers which had developed such programs.

#### e. Interdata

CFA licensing terms dominated the concern over the selection of the 8/32. (See Volume VII) Concern continued over the support software. Although the Interdata was shown to have half the software base of the S/370, the software study did not take into account the maturity or diversity of the software. For example, a newly released Fortran compiler would have counted equivalently to 10 well tested compilers, some of which might produce optimized code, while others might have fast compilation times for program development. The strong showing of the 8/32 in the test program results and its efficient I/O characteristics are indicative of the fact that it was designed for control and communications applications.

#### 5. SUMMATION

The issues were summarized for each architecture by the various Architectural Subcommittee Chairmen.

	<u>For</u>	<u>Against</u>
<u>PDP-11</u>	Large implemented range Experience with OEM systems Experience with distributed systems Good performance on life cycle cost models Good interrupt structure Cooperative manufacturer	Small virtual address space problem
<u>S/370</u>	Large software base Very precise definition of the architecture Virtual Machine Operating System supported	I/O interrupt response Least efficient on test programs Subsetability
<u>8/32</u>	Most efficient on test programs Architecture with room for expansion Good interrupt structure	Weak support software Weak performance on life cycle cost model Licensing No virtual machine capability

## 6. FINAL SELECTION/RECOMMENDATIONS

A vote was taken for the third place architecture, in order to maximize the possibility of getting a two thirds majority on the selection of the final candidate. The vote was:

16 Interdata 8/32  
1 PDP-11  
1 not present

The final vote for best architecture was:

14 PDP-11  
4 S/370.

The committee had four final recommendations:

a. The committee unanimously agreed that a single instruction-set architecture should be selected for the MCF, that the selection of only one architecture is more important than which one of the three final candidate architectures is selected, and that any one of the three could provide a satisfactory basis for the MCF.

b. The DEC PDP-11 was determined to be the most advantageous architecture for the MCF, the IBM S/370 was ranked second, and the Interdata 8/32 was ranked third.

c. The committee agreed that an effort should be made to correct the limitations of the selected architecture.

PDP-11: Small address space  
Floating point instruction compatibility

S/370: I/O  
Low end subsetability

Interdata 8/32: Complete study of interrupt/trap recovery  
Virtualizability

d. A single organizational structure must be established to control the architecture, otherwise major incompatibilities between different implementations will surely result.

Also, it is clear that the military's involvement in architectural questions cannot end with the CFA final selection. If architectural control is lost at any time during the life-cycle of the CFA project, the problems the CFA was conceived to relieve will remain and the results will be little better than the situation that exists prior to CFA.